AD-A105 236 UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES DEPT O--ETC F/G 20/4
ON THE MANIPULATION OF SPREADING RATES OF FORCED MIXING LAYERS.(U)
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ON THE MANIPULATION OF SPREADING RATES OF FORCED MIXING LAYERS

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ABSTRACT

The vortex merging in a mixing layer can be modified by applying periodic forcing at the origin. When the forcing parameters (frequency, amplitude as well as phase difference between fundamental and subharmonic) varies, the pattern of vortex merging changes. Consequently, the spreading rate of the mixing layer can be manipulated. The effect of each forcing parameter on the change in the spreading rate is discussed in the present paper.

NOMENCLATURE

$E(f)$ - Integrated value of $U'(f)$ across the mixing layer
f_c - most amplified frequency
f_f - forcing frequency
f_r - response frequency
R - velocity ratio $R=(U_1 - U_2)/(U_1 + U_2)$
U_1 - mean velocity at high speed side U_1 = 8.5 cm/sec
U_2 - mean velocity at low speed side U_2 = 1.32 cm/sec
$\bar{U}$ - average velocity $\bar{U} = (U_1 + U_2)/2$
$U(f)$ - narrow band streamwise energy content
$U'(f)$ - $U'(f) = U(f)/\bar{U}$
θ_o - initial momentum thickness θ_o = 0.116 cm
θ - momentum thickness
β - phase difference between subharmonic and fundamental
λ - initial instability wavelength $\lambda = \bar{U}/f_o$

Introduction

While a mixing layer is under external forcing, the formation and merging of coherent structures are localized. The role of coherent structures in the dynamics of a mixing layer can be easily examined because the randomness is removed. In addition, physical insight into the vortex merging process can be explored by varying the forcing parameters. The spreading of a mixing layer is caused by the merging of vortices (1). Therefore, the spreading rate can be manipulated by modifying the vortex merging. This is important in many technical applications. In the case of combustion, larger spreading means higher entrainment (2) and better chemical reaction efficiency. When the vortex merging is modified, the far field noise radiation is also significantly changed (3).

The initial formation and merging of the vortices are governed by the stability process of the mixing layer (4,5). The instability behaves like a band pass filter (6,7) which amplifies perturbations in a band of preferred frequencies and damps perturbations outside this band. The effective forcing frequency should be close to the most amplified frequency, so that the low level perturbations can be easily amplified and eventually modify the development of the mixing layer (5). Furthermore, the vortices, not the random small scale turbulence are to be controlled. Therefore, the effective forcing function should be spatially and temporally coherent. There is an infinite number of possible coherent and periodic wave forms that can be applied to force the mixing layer, but the band pass filtering characteristics usually select a few frequency components and their harmonics from the forcing waves. For example, if a pulse train is used, the mixing layer will only respond to the harmonics close to the most amplified frequency. Hence, we will limit our discussion to the sinusoidal perturbations or sinusoidal waves with its harmonics and subharmonics.

EXPERIMENTAL FACILITIES

The experiment was performed in a water channel with a 10 cm wide, 10 cm high and 180 cm long test section (Fig. 1).

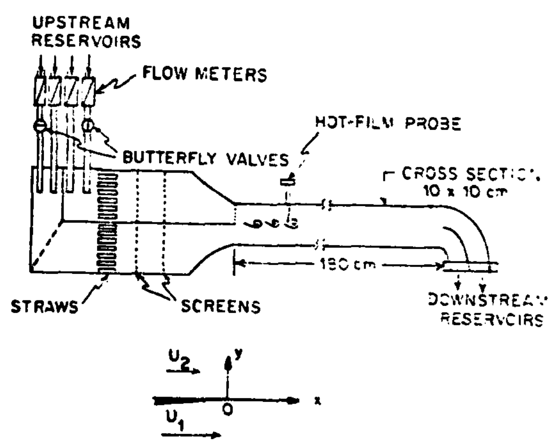

Fig 1 Water channel

The stagnation chamber is separated into two compartments. The splitter plate ends with a sharp trailing edge at the beginning of the test section. Two supply

pipes control the mean flow rate with flow meters (Fisher Porter Type 10A3565AY) in two streams. Another two supply pipes provide the perturbations by using butterfly valves. While the effect of the frequency is studied, both butterfly valves rotate at the same frequency. The output is fed into each compartment. While the effect of the phase difference is studied, one butterfly valve rotates at exactly half of the frequency of the other valve. The output of both of the pipes are fed into the high speed compartment. At this point, both the fundamental and the subharmonic are provided by the forcing. The phase difference between the fundamental and the subharmonic are varied by changing the angle of the two blades in the butterfly valves. The phase difference, β, is defined as the angle of the fundamental led by the subharmonic. The amplitude of the forcing is adjusted by two flow meters located downstream of the butterfly valves.

The velocity is measured by a hot-film probe (TSI-TYPE 1210) and visulized by food coloring. Data are recorded on an analog tape recorder (HP TYPE 1040A) and then digitized and processed on a PDP 11/55 computer.

THE FORCING FREQUENCY

The response of a mixing layer under perturbations of a wide range of forcing frequencies was studied and reported on in a separate paper. The results are summarized as follows: when the mixing layer was forced at the frequency f_f, one of the harmonics of the forcing frequency was close to the most amplified frequency and amplified very quickly. Downstream from the splitter plate, the vortices evolved from the stability waves and formed at the specific harmonic f_r. When the forcing frequency changed from higher than to much lower than the most amplified frequency, the response frequency formed four frequency stages, modes, in the present experiment. At each frequency stage, the forcing frequency is the Mth subharmonic of f_r and there were M vortices in each subharmonic wavelength. Further downstream, the subharmonic amplifies and laterally displaces the M vortices. Due to the lateral velocity gradient and mutual induction, M vortices will eventually merge into a single coherent structure. A very large spreading has been achieved. In the same frequency stage, if the mixing layer was forced at a higher frequency, a thinner initial mixing layer and earlier vortex merging were observed (5). When the mixing layer was forced near the most amplified frequency, the vortices formed at equal distances and strengths. The subharmonic is suppressed and thw vortex merging is significantly delayed (5). Apparently, the subharmonic is an essential catalyst in order for vortex merging to occur. Vortex merging is caused by the interaction between the fundamental frequency, f_r, and the Mth subharmonic frequency, f_f. The forcing level required in the multiple vortex merging is very low, 0.01% to 0.1% of $\bar{U}$, because the amplification of the subharmonic is via the instability. Only a very small amount of "seed" energy is needed.

Multiple vortex mergings are also observed in jets under forcing conditions (2,8). From dye visualization, the entrainment is seen to be closely related to the merging process (2).

When the forcing frequency is very low, (say about one tenth of f_r), a great many vortices can coalesce, if the forcing amplitude is high. This phenomenon is termed "collective interaction" (5,9). This mechanism was found to be an important link in the phase locked feedback loop of a resonant impinging jet. Two characteristics associated with the collective interaction are a large spreading rate and a sharp drop in the passage frequency.

A very large spreading rate occurs when the mixing layer is forced by a flap oscillating at a frequency much lower than the most amplified frequency (10). The large spread should be the consequence of the collective interaction mechanism.

SUBHARMONIC AND VORTEX MERGING

The vortex merging can be either enhanced by providing subharmonic forcing or delayed by suppressing the subharmonic. The merging process should be related to the amplification of the subharmonic. It has been observed (5) that the two vortices become vertically aligned at the location where the amplifying subharmonic reaches its peak (Fig. 2).

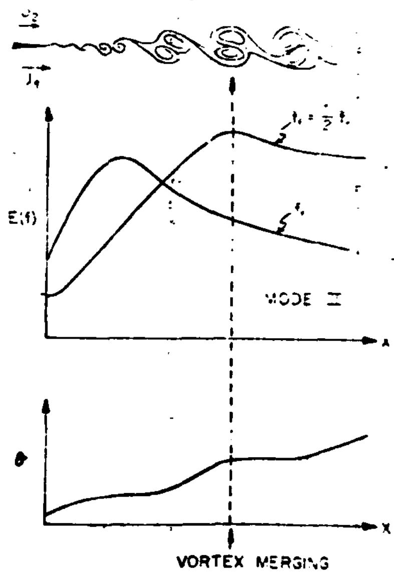

Fig. 2 The location of vortex merging

At the same location, the thickness of the mixing layer stops growing until further merging takes place. Based upon these features, we define this specific location as the position of vortex merging. Furthermore, the position of vortex merging is found to occur at an integer number of instability wavelengths (5). This result supports the conclusion that the global feedback mechanism plays an important role in determining the location of vortex merging (9,11,12). The exact number of instability wavelengths needed to accomplish a merging is inversely proportional to the velocity ratio or to the maximum amplification rate (15). Hence the location of vortex merging is also controlled by the local stability process.

THE PHASE DIFFERENCE

From analytical studies (13) and numerical experiments, (14,15) it has been realized that the phase difference between the fundamental and the subharmonic can greatly change the energy transfer between the two frequencies. The pattern of vortex merging is consequently different. The evolution of the vortices can change from merging to shredding (14,15) as a function of the phase angle. In the laboratory experiment, significantly different merging patterns were observed in the cases where merging involved three and four vortices, due to the phase difference.

At present, the phase difference can be controlled by varying the angle between the two blades of the butterfly valves. The amplification of the subharmonic and fundamental are measured and visualization experiments are also performed.

While β is in the first two quadrants, the formation of the vortices and the position of the merging are fairly localized. $\beta \approx 90^{\circ}$ seems to be the optimal condition for localizing the merging. Similar results have been found in the numerical simulation (15). While β is found in both the third and fourth quadrants, significant randomness of vortex mergings are observed. However, the vortex shredding is rarely obseved. Perhaps this is because the shredding mode is itself very unstable. A small amount of noise at the subharmonic frequency is significant enough to change the phase angle and results in a merging instead of a shredding.

Two cases with $\beta = 90^{\circ}$ and 270° have been quantitatively studied. The narrow band streamwise energy contents, U (f), were measured across the *mixing* layer at many downstream locations. The normalized values of U (f) are integrated across the layer.

$$E\ (f) = \frac{1}{\theta_0} \int_{-\infty}^{\infty} \frac{1}{2} \left(\frac{U\ (f)}{\bar{U}}\right)^2 \ dy \qquad (1)$$

and plotted as a function of distance (Figs. 3 and 4).

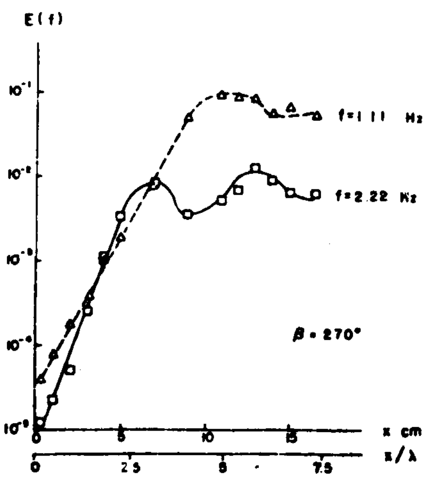

Fig. 3 The amplification of E·(f) $\beta = 270^{\circ}$

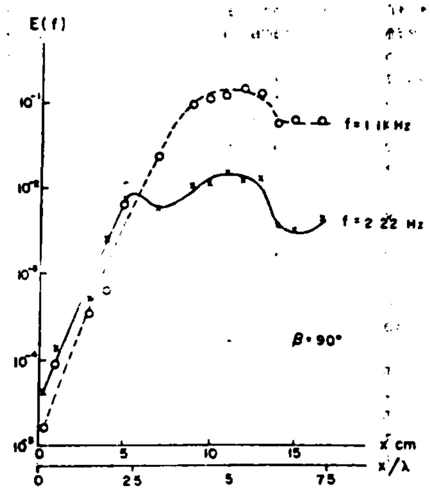

Fig. 4 The amplification of E (f) $\beta = 90^{\circ}$

The amplification rates of the fundamental at both phase angles have the same value which agrees well with the inviscid stability analysis (7). The amplification rates of the subharmonic are quite different in two cases. While $\beta = 90^{\circ}$, the vortex merging is optimally localized, and the amplification rate of the subharmonic can be the same as that of the fundamental. While $\beta = 270^{\circ}$, the vortex merging is not localized and the amplification rate is significantly reduced. Apparently, the amplification rate is a fairly strong function of the phase difference. The profiles of U' (f) at several streamwise locations are plotted (Fig. 5,6). Near the trailing edge, where the amplitude is low, x = 1 cm, and downstream where the amplitude is high, x = 5 cm, the profiles always keeping a two peak characteristic as is predicted by the stability theory. The patterns of the profiles change quite a bit after the fundamental or subharmonic reach their peak (Fig. 6).

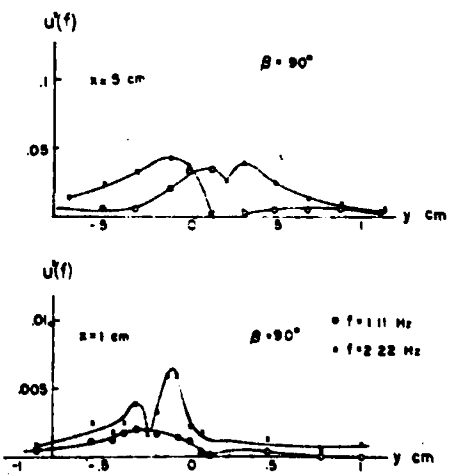

Fig. 5 The profiles of U' (f) $\beta = 90^{\circ}$

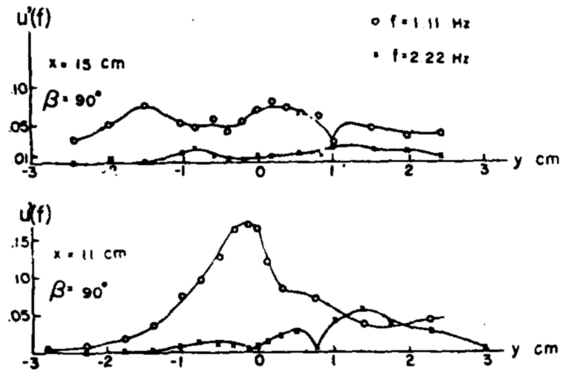

Fig. 6 The profiles of U' (f) $\beta = 90^{\circ}$

Even larger changes have been observed further downstream.

THE FORCING AMPLITUDE

In visualization experiments, the position of vortex merging moves upstream with increasing forcing amplitude. This general trend is in line with the results discussed in Figure 3, because the subharmonic will reach its peak sooner with a higher initial forcing amplitude. However, not enough quantitative experiments have been performed in studying this aspect. Several basic questions need to be verified; does the peak value of E (f) change with the forcing level? Does the gain in amplification vary with the forcing level? If these questions can be answered, the effect of the forcing amplitude on vortex merging can be deduced by the following discussion of Figure 3.

For fundamental waves in a forced jet, the peak values of E (f) change with the forcing level (16). The gain in amplification is constant for low forcing levels, but not for high forcing levels. For the subharmonic in a forced jet (2), the peak values of E (f) seem not to stay constant. Furthermore, the results in Figures 4 and 5 show that the gain also varies with the phase angle. This experimental evidence answers part of the questions, but more experiments are definately needed in order to study the effect of the forcing amplitude. However, we should be aware that if the range of the forcing amplitude is limited to low levels, the location of merging should not be significantly changed. The amplification gained is very large within one wavelength, a small function variation of the initial forcing amplitude should not advance or delay the position of merging very much as compared with one wavelength.

CONCLUSION

The pattern of vortex merging can be modified by applying a coherent forcing function to the mixing layer. The variation of parameters of the forcing function does alter the vortex merging. While the Mth subharmonic of the most amplified frequency is provided in the mixing layer, M vortices can merge simultaneously which results in a large spreading rate. Some preliminary results show that the amplification rate of the subharmonic changes with the phase angle between the subharmonic and fundamental to a large extent, but the amplification rates of the fundamental stays constant. The pattern of vortex merging is observed to change with the phase angle. With higher forcing amplitudes, the position of vortex merging was observed to move upstream. More quantitative studies are needed in order to better understand the effects of the forcing level. However, large effects on the merging location is expected only if the forcing level is extremely high.

ACKNOWLEDGEMENT

This work was supported by the Office of Naval Research, Contract Number N00014-77-C-0314.

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1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A105236	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ON THE MANIPULATION OF SPREADING RATES OF FORCED MIXING LAYERS.		5. TYPE OF REPORT & PERIOD COVERED Technical 7/1/80 - 6/30/81
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ho, Chih-Ming and Zhang, Yu-Quan		8. CONTRACT OR GRANT NUMBER(s) N00014-77-C-0314
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Southern California Aerospace Engineering Department Los Angeles, California 90007		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Dept. of the Navy Office of Naval Research Fluid Dynamics Program Arlington, Vriginia 22217		12. REPORT DATE Sep[redacted]981
		13. NUMBER OF PAGES 3
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Office of Naval Research Department of the Navy 1030 East Green Street Pasadena, California 91106		15. SECURITY CLASS. (of this report) Unlimited
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Free shear layer Subharmonic forcing
Spreading rate
coherent structure

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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